PARAMETRIC INVESTIGATION OF MICROWAVE-ASSISTED MATERIALS PROCESSING

Synopsis of the PhD Thesis

Submitted by

Praveen Kumar Loharkar

(Roll No. P012)

Department of Mechanical Engineering

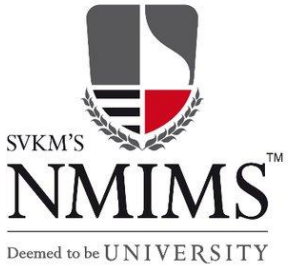
Supervisor

Dr. Asha Ingle

Professor and Head, Department of Mechanical Engineering

submitted in partial fulfilment of the requirements of

DOCTOR OF PHILOSOPHY (Engineering)



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SVKM's NARSEE MONJEE INSTITUTE OF MANAGEMENT STUDIES (Declared as Deemed-to-be University Under Section 3 of the UGC Act, 1956)
V. L. Mehta Road, Vile Parle (West)
MUMBAI –400056

2023

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ABSTRACT

Keywords: Coating; Joining, Microwave, Simulation; Susceptor

Microwave is a unique constituent of the electromagnetic spectrum characterized by longer wavelengths with an ability to generate heat within a material. Microwave heating is a unique phenomenon which has a substantial untapped potential in the field of materials processing. Microwave heating comes with many advantages in materials processing domain which primarily includes faster processing times and minimal environmental impact. Its use was limited to ceramic drying and sintering applications until it was demonstrated that metals can be processed using microwaves by using an indirect heating. Even though several applications of microwave energy in materials processing domain have been reported, its industrial use is still not popular. This can be attributed to very limited understanding of the microwave heating phenomenon and dedicated devices to use microwave irradiation in materials processing. Furthermore, numerical simulation of microwave heating and investigation of the parameters having potential effect on the microwave heating is still a widely open domain of research.

This work has been carried out in three major phases. In the first phase, parametric numerical simulation was carried out to compare three important microwave susceptors identified from the literature, viz. silicon carbide, alumina and coal on the basis of temperature rise. Out of the three susceptors, coal attained highest temperature (901 ^{o}C) upon interacting with microwave radiation. However, it was also noted that the temperature distribution in coal was non-uniform owing to poor thermal conductivity. To quantify the impact of input parameters such as incident power, position of the material inside the microwave cavity and the time of microwave irradiation, regression models were developed for estimating temperature rise in each of these susceptors. These models were found to be statistically significant.

The results of numerical simulation led to better understanding on the susceptor characteristics. This was further utilized to carry out experimental trials on an industrial polymer coating process comprising of a furnace curing step in the process route. The simulation methodology was used to select a susceptor for devising set-up for curing the electrostatically sprayed polymeric powder onto a metallic substrate. Here, based on simulation, a graphite susceptor was chosen, as the temperature rise generated by the graphite susceptor is 200 ^{o}C. This is sufficient for the curing

process. Taguchi L9 orthogonal array was used for experimental design with three factors. Three factors, voltage (kV), powder flow rate (g/min.) and microwave power (W) were used at three levels. The effect of these factors on gloss units; used as a measure of appearance, impact strength and corrosion resistance was assessed. The results illustrated that microwave power has the most significant impact followed by voltage and powder flow rate on the properties of the coated specimens. In addition, characterization results of the coated specimens demonstrated feasibility of microwave curing as a replacement of conventional curing process leading to reduction in process time.

A customized device was designed and fabricated for joining of metallic plates using microwave energy with several features to overcome limitations of temporary set-ups mentioned in the literature. Few of these limitations were absence of a clamping mechanism, use of domestic ovens with little or negligible control over microwave irradiation, use of susceptors such as charcoal which burn out after a trial etc. A patent has been filed and published on the customized joining device based on microwave energy. This device was further utilized to check the feasibility of joints of non-ferrous materials such as aluminium alloys and pure copper. The prepared joints were mechanically tested and characterized. An important observation was that due to the concentration of microwave heat around the fusion zone, a very small region of heat affected zone is formed.

The key contributions of the work include development of detailed understanding of the microwave processing parameters and extended factors that have an impact on the related applications. In addition, prediction of temperature rise in the susceptors using regression models and their comparative analysis based on numerical simulation led to significant inferences on susceptor selection and their microwave-interaction behaviour under parametric variations. This led to development of coating application for an industrial polymer coating process which also involved parametric study on the process parameters which led to encouraging results. Another important part of the work was development of customized device for joining of materials using microwave energy with increased control over the process. This was further used to develop understanding on joining aluminium alloys and tin-plated copper plates.

The work can further be extended to identify suitable combination of filler and base metals for obtaining high strength joints using microwave energy. A dedicated microwave-based curing

apparatus in conjunction with the electrostatic process can also provide an energy efficient and environment friendly alternative to furnace heating.

1. Introduction

Processing materials using microwaves has been a significant advancement in the broad field of manufacturing. The manufacturing processes requiring thermal energy can use microwave radiations as a source of heat. Microwave energy exhibits several advantages when it is used in thermal applications, which includes uniform heating across the bulk material, cleaner energy conversion and short processing times. This has led to development of several processing applications such as drying, sintering, material joining, coating, cladding, and casting [1–3].

Successful use of microwave energy in the applications stated above have established the efficacy of microwaves in materials processing domain. The process and product characteristics attained in microwave processing have been encouraging. With the ever-growing urge for limiting the use of conventional heating sources such as fossil fuels, extensive use of microwave energy in manufacturing applications can build a path for green processing technologies and reduced environmental impact.

However, transformation of microwave energy into heat is a challenging proposition. The detailed description on the parameters that govern the heating efficiency and transformation of microwave energy to the thermal energy has been presented in the literature review section. In the following section, the problem identified for the research work has been presented.

1.1 Problem Description

Even though microwave-assisted process has demonstrated several merits, the development in this field has been relatively slow over the years. The reason being poor interaction of microwave radiations and metals. Since bulk of the manufacturing processes involve metals as the key constituent, the use of thermal capability of microwaves in metal-based processing is limited. The rate of progress has become faster after the methodology for processing metals inside the microwaves was evolved around the year 1999 [4] . Thereafter, several researchers started exploring methods to process metals using microwave energy. However, through the literature review it was identified that majorly, industrial case-studies on using microwave energy are limited. An important reason or rationale for limited industrial applications is limited knowledge

on susceptor selection and corresponding temperature rise, limited parametric studies and unavailability of a dedicated device for specific applications. Thus, to leverage the use of this potentially energy efficient and green materials processing technique, it was important to demonstrate its use and feasibility in an industrial context. Similarly, a methodology was required to explore the relative heating characteristics of various popular susceptors. In addition, development of a customized device for an application such as material joining with a provision to control process parameters and easy operability was another significant problem identified.

1.2 Research Objectives

1. To identify important parameters of microwave-assisted processing and compare susceptors materials using parametric numerical simulation.
2. To devise a methodology for curing of polymer coatings using microwave energy and perform investigation on the coating application.
3. To carry out characterization of the coated specimens and evaluate the effect of microwave processing on the coating characteristics.
4. To design and develop customized joining device for joining non-ferrous materials using microwave energy and perform joining application.
5. To carry out characterization of the joints and evaluate the effect of microwave processing on the joint characteristics.

1.3 Contributions

Contributions of the research work have been summarized below.

1. Identified microwave-assisted materials processing parameters important to the control of microwave heating.
2. Proposed regression models for the temperature rise in silicon carbide, coal and alumina, which are prominent susceptor materials using numerical simulation.
3. Conducted comparative analysis of the susceptor materials to demonstrate their utility in material processing applications.
4. Developed and proposed a set-up for curing of polymer coating of metallic substrate using microwave energy as a potential alternative to existing furnace heating used in an industry.

5. Investigated the parametric effect of microwave-assisted curing process on the gloss, impact strength and corrosion resistance of the powder coated specimens.
6. Designed and fabricated a customized device for joining non-ferrous metallic plates using microwave energy.
7. Demonstrated joining of non-ferrous materials such as AA6061 and Copper in the customized device and identified the typical issues during joining using microwave energy.

2. Literature Review

The review is segmented in two sections. The first deals with the parameter description while the second section presents an account of work related to surface modification and joining using microwave energy.

2.1 Parameters in Microwave Heating

Materials processing in general is significantly influenced by the parameters and thus it is important to ascertain these to be able to keep a close control on the entire process. Microwave is an electromagnetic source of energy and hence, the heating phenomenon is grossly influenced by the properties such as dielectric strength and magnetic permeability and other related properties. Based on an extensive review, it was identified that there are four prominent parameters that affect the outcomes of microwave-assisted processes. These parameters are:

i. Material Properties: Dielectric and magnetic properties
ii. Heating Mechanisms
iii. Load being processed
iv. Applicators used for heating

Figure 2.1 shows these parameters with the factors that govern them. The effect of these factors on the parameters and consequently the microwave-assisted heating processes has been discussed in detail.

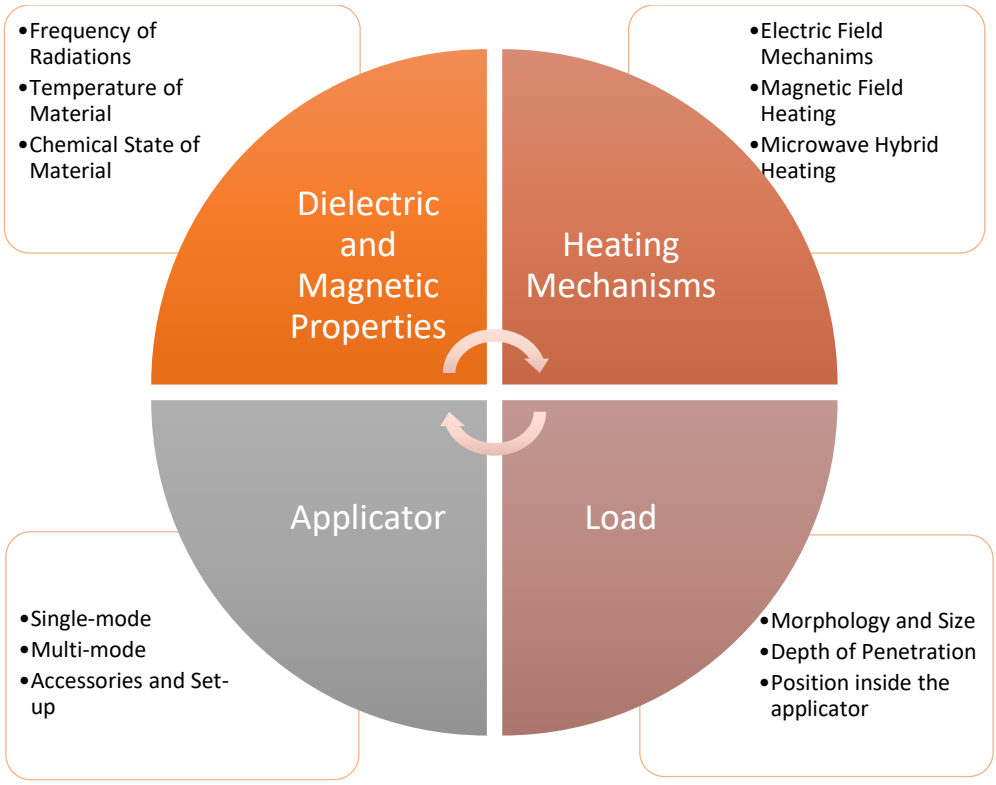


Figure 2.1 Parameters and factors affecting microwave-assisted heating processes

The dielectric and magnetic properties are affected by microwave frequency and specimen temperature. However, the frequency of microwaves is confined to specific values, such as 2.45 GHz used in domestic ovens which are laid down by the regulatory bodies [5,6]. This is to avoid interference with the microwaves used for telecommunication applications. Secondly, the temperature is governed by the process requirement. Therefore, to enhance rate of heating, the factor which can be controllably varied is the composition of materials. In case the material to be processed cannot be altered, other materials with better interaction capabilities can be used in conjunction with the specimen material to be heated.

As stated earlier, a significant challenge with respect to microwave-assisted processing of materials is the fact that many important engineering materials do not couple with microwaves. In fact, these materials reflect the radiations completely. This is very much a case for metals which have high electrical conductivity.

Hence, materials such as silicon carbide, charcoal, coal, graphite, and zirconia are used as susceptors. These materials interact with microwaves and due to the mechanisms discussed, generate the heat that can be employed for processing application. This results in indirect heating

and is depicted as hybrid heating in literature [7]. These susceptor materials can be chosen as per the condition of the process heat requirement. Moreover, there is still a very little understanding on the mechanisms of heat generation in different materials. Therefore, mathematical modelling of microwave heating can go a long way in the field of microwave-assisted processing research to achieve better reliability and of process outcomes.

Another important parameter in microwave heating is the material specimen that gets exposed to the microwave irradiation. It is termed as “Load.” This load is kept in the microwave cavity and exposed to microwave radiations and unlike conventional processing, it also influences heating in general and temperature rise. There are a few factors that govern the heating of “Load.” Three of these significant factors which are to be concentrated upon are penetration depth – a key factor reliant on the electrical conductivity of the load material, size of the load, and positioning of the load inside the microwave applicator [5].

Last important parameter identified for processing materials is the design of microwave applicators. These are the devices wherein the load is positioned for carrying out processing using microwave irradiation. Key factors related to microwave applicators are the type of applicators which primarily are two: one is single-mode and the second one is multi-mode. In addition to the types, the design of microwave cavity and its size also have a direct impact on the microwave heating and subsequently the process efficiency. All these factors govern the microwave power availability for material processing [8]. In different studies, it has been expressed that development of customize applicators is critical to improvement in concentrating microwave power on the load [9].

Based on the above literature review on microwave heating parameters, it has been inferred that metal processing using microwaves derives its complexity from the factors that influence the transformation of energy from electromagnetic form to the thermal form. In addition, the challenges become more prominent when the overall process is governed by two broad physical phenomena. One is related to generation and propagation of microwave radiations and the other one is conversion of microwave energy to heat and subsequent transfer of this heat under different modes of heating.

2.2 Material Processing using Microwaves: Related Work

Materials processing using microwave was first illustrated using sintering application [3]. However, in past two decades there has been rise in the use of microwave energy for applications such as coating, cladding, joining and casting [10,11] .

Surface modification using coating or cladding is one of the most sought-after material processing applications as it involves enhancement of functionality of a component without drastic increase in the cost of material. Enhanced understanding of microwave heating led to extensive investigations on developing coatings and claddings by utilizing the thermal capability of microwave radiation [12–14]. In this context, Gupta and Sharma [11] presented the methodology and results for cladding application. Cladding material, EWAC which has 97% nickel was melted and cladded uniformly over the substrate of austenitic stainless-steel. The experiments were executed inside a set-up built within a domestic oven rated at 1 kW and operated at a microwave frequency of 2.45 GHz.

The ability of microwaves to impart uniform heating on surface have resulted in strong and thermal-stress independent clads and coatings [7]. However, the researchers have limited their study to the laboratory scale [15–17]. Secondly, it was found that there is a scope for parametric studies to understand the effect of process parameters on the functional properties of the cladded or coated specimens.

Joining using microwave energy another important development in processing using microwave energy that uses the indirect heating phenomenon for joining of metallic specimens. Pioneering work in the field joining of materials using microwave energy was done by Siores and Rego [18]. It has been stated that use of microwave heating minimizes the energy consumption by 10-100 times while the process time reduction by 10-200 times. The materials were plastics, metals of very small thickness (0.1 mm - 0.3 mm) and ceramics which were joined either with or without bonding agents or adhesives under the influence of microwave energy. The work demonstrated the feasibility of joining process using microwaves. One of the key breakthroughs in the joining using microwave was successful demonstration of hybrid heating in joining bulk stainless steel alloy plates by Srinath and Sharma [19]. A conventional oven having rated microwave power of 900 W and a frequency of 2.45 GHz was used to conduct the experiments. The joint was arranged as a square butt and filled with a nickel based powder of particle size 40 microns. These experimental

trials were carried out under atmospheric conditions and the joint arrangement was irradiated for 390 seconds. Charcoal was used as a susceptor due to its susceptibility to microwaves. Carbon rich charcoal undergoes rapid heating as a result of Maxwell-Wagner effect which is explained by Sun et al. [20]. Bansal et al. [21], worked on the similar base metal that is, SS 316. However, instead of using Ni-based filler powder, SS 316 filler powder was used. The microstructure obtained after characterization revealed uniform bonding at the interface of filler and base metals. Clamping force was not used during the joining process. High microhardness was observed at the junction of base metal and filler material due to the presence of martensitic structure and precipitation of carbides. In continuation to the experiments on the use of microwave joining of similar metals, dissimilar joining of SS 316 and MS was performed by Srinath et al. [22] with an aim to characterized the processed joint for microstructure and mechanical properties. The experimental conditions, viz. microwave power (900 W), susceptor (charcoal), atmospheric environment etc. were similar to the experiments performed in joining SS 316 plates. Due to near complete melting of interface powder, the joints had superior strength and enhanced elongation.

Gamit et al. [23] used the concept of microwave heating in hybrid mode to join pipes of mild steel having inner diameter of 10 mm and thickness 2 mm each and lengths of 20 mm for the lower pipe and 30 mm for the upper one. Microwave irradiation at a power of 900 W and frequency 2.45 GHz was used to generate the thermal energy required to melt the interfacing Ni used as a filler material in the powdered form. The joint exhibited greater micro-hardness than the base metal region. Porosity was observed at the outer side of the joint due to the interaction of gases at the junction. It was inferred that exposure time and particle size play an important role in joint quality. For instance, smaller particle size results in better microwave interaction.

From the published literature, it was inferred that most of the work has been carried out in a conventional microwave oven which limits the control and reliability over the joining process. In addition, joining of aluminum alloys have not been extensively studied.

Thus, on the basis of literature review, problem statement stated in the section 1 was formulated along with the objectives and the following methodology was devised and adopted.

2.3 Plan of work

The work has been conducted in four phases as shown in the Figure 2.2.

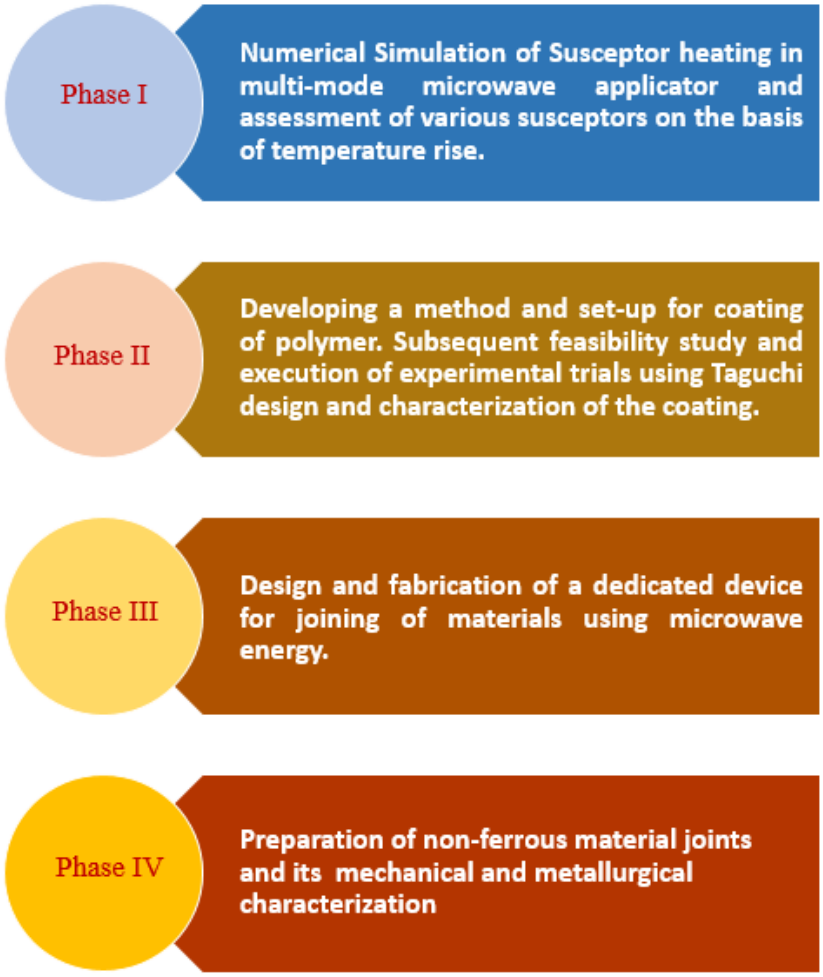

Phase I
Numerical Simulation of Susceptor heating in multi-mode microwave applicator and assessment of various susceptors on the basis of temperature rise.
Phase II
Developing a method and set-up for coating of polymer. Subsequent feasibility study and execution of experimental trials using Taguchi design and characterization of the coating.
Phase III
Design and fabrication of a dedicated device for joining of materials using microwave energy.
Phase IV
Preparation of non-ferrous material joints and its mechanical and metallurgical characterization

Figure 2.2 Phases of research work

3. Numerical Analysis of Microwave Heating of Materials

In this chapter, use of numerical simulation for understanding the parametric effects on heating of susceptors has been demonstrated. Following section elaborates on the physics involved in the conversion of microwave energy to thermal energy and the methodology used in the simulation.

3.1 Fundamentals of Power dissipation and Heat Transfer

Microwave radiation's heating capability is attributed to the conversion of microwave energy into thermal energy. The exchange rate of heat generated per unit volume due to microwave energy in

dielectric materials is given by equation 3.1 and in conducting materials is given by equation 3.2 [24].

$$Q_{em}(\mathrm{x,y,z,t}) = \omega\varepsilon_0\varepsilon'' E_{\mathrm{rms}}^2 \quad (3.1)$$

$$Q_{\mathrm{em}}\ (\mathrm{x,y,z,t}) = \sigma E_{\mathrm{rms}}^2 \quad (3.2)$$

Equations 3.1 and 3.2 express the loss in power per unit volume. In other words, heat generated per unit volume due to the conversion of electromagnetic energy into thermal energy, in terms of RMS (Root Mean Square) of the intensity of the electric field in the region with local coordinates *"x, y, z"* and time "*t*."

The distribution of temperature in the load (material being heated) is governed by the "heat transfer" equation based on the thermo-physical properties of the material subjected to microwave heating [25,26]. Equation 3.3 expresses the heat transfer rate.

$$\rho C_p \frac{\partial T}{\partial t} = \nabla(k\nabla T) + Q_{\mathrm{em}} \quad (3.3)$$

The unified solution of equation 3.1, equation 3.2 and equation 3.3 along with the Maxwell's equations govern the distribution of temperature and the distribution of electric field across the material being irradiated. This requires a multi-physics simulation approach.

3.2 General Steps of Simulation

Figure 3.1 shows a general flow diagram for the computer modelling of microwave heating. The first stage is to build a model, either in 2D or 3D, that depicts the setup's precise physical geometry. It consists of the waveguide, the port, the oven cavity, the material to be processed, and other elements of the heating setup. When the load (processed material) is symmetrical, 2D analysis can be used. The 3D model is still the better option to seek more accuracy of the simulation outcome.

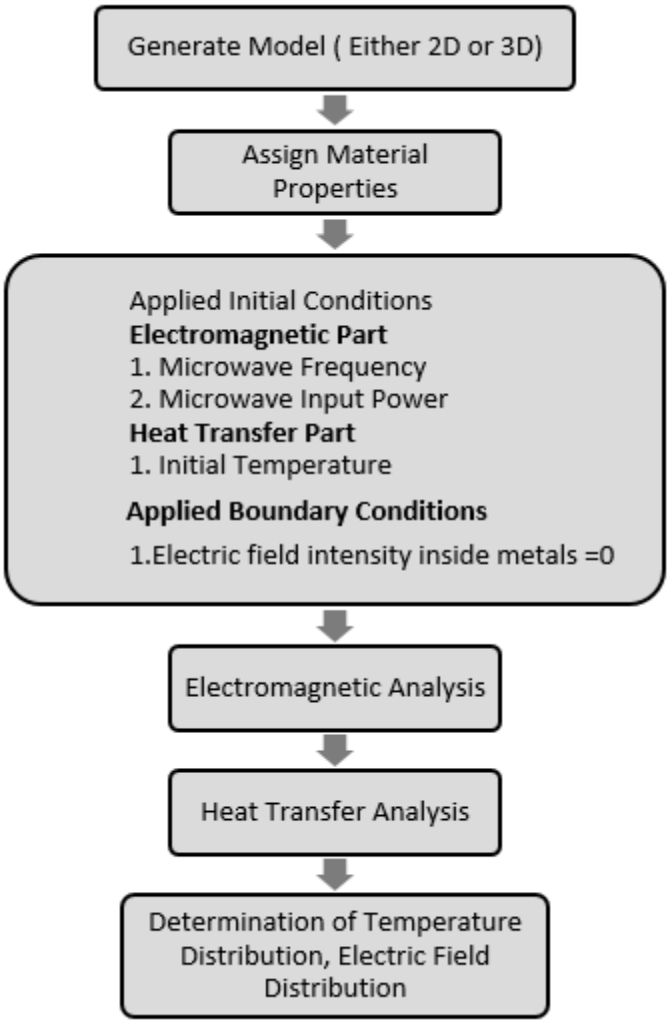


Figure 3.1 Flow diagram of numerical simulation of microwave heating

3.3 Summary of the Chapter

Selection of an appropriate susceptor is a challenging task in a microwave processing application involving metals. Hence, to identify suitable susceptors for subsequent experimental work, comparison of three well-known susceptors, silicon carbide, alumina, and coal was done using an electromagnetic analysis coupled with heat transfer analysis to determine the maximum temperature that can be attained. Figure 3.2 shows the temperature distribution in the three chosen susceptor blocks. The highest temperature obtained was 901 ^{o}C for coal, followed by 615 ^{o}C for alumina and 529 ^{o}C for silicon carbide. It is critical to note that even though coal resulted in highest magnitude of temperature, its poor thermal conductivity results in the creation of hot patches and

uneven temperature fields. Both of these are undesirable and unsuitable for hybrid microwave heating.

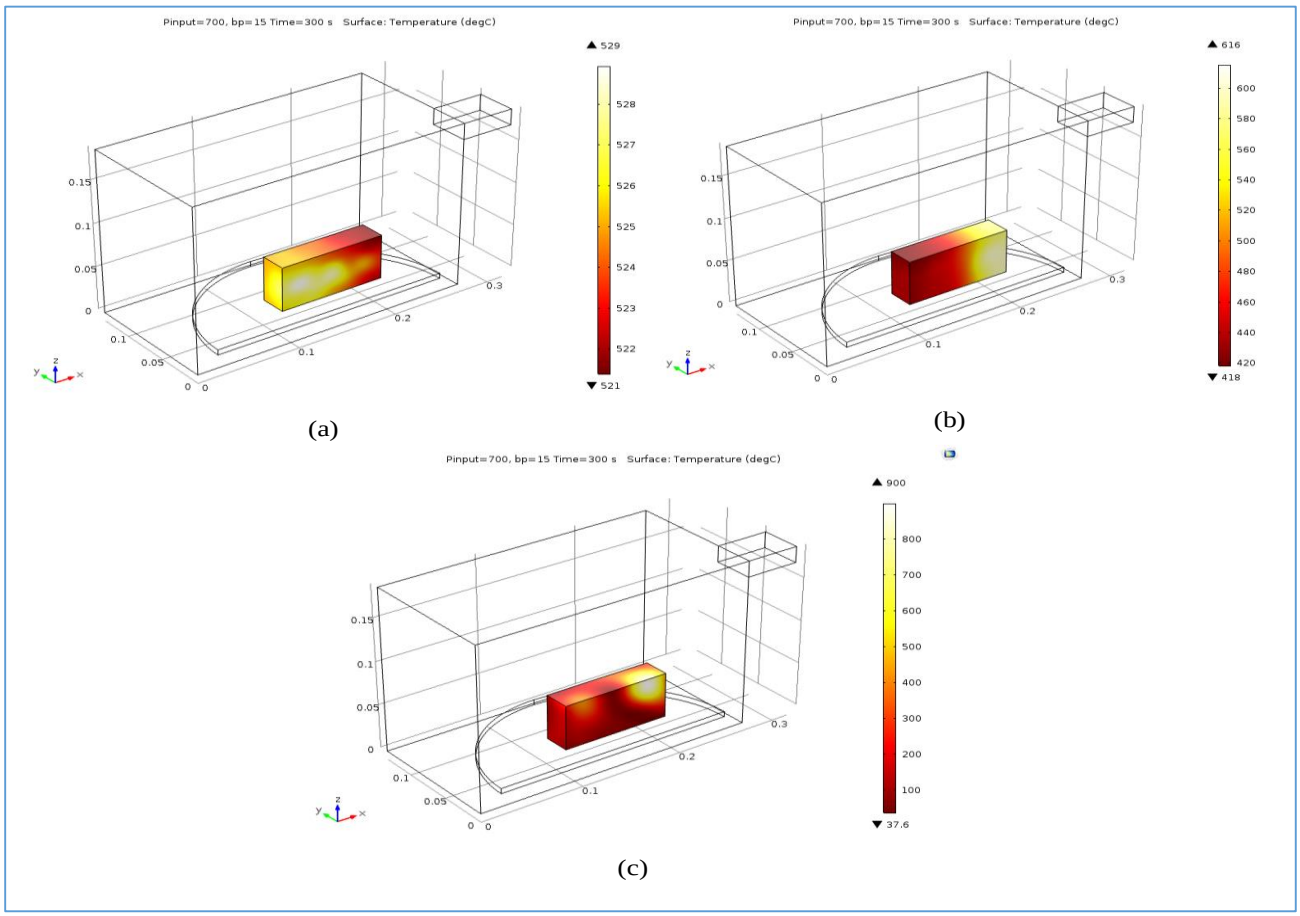


Figure 3.2. Temperature rise in (a) silicon carbide, (b) alumina, and (c) coal at P_{input} = 700 W and t =300 s and h=15 mm

It was also inferred that the maximum temperature values are greatly influenced by both the position of the susceptor block and the microwave power. These two parameters have been determined to be the two most important influencing elements in microwave heating. Figure 3.3 shows the comparison between the three susceptor blocks as a function of power input. To determine temperature as a function of selected parameters, regression analysis for the temperature rise in the susceptor blocks has also been done.

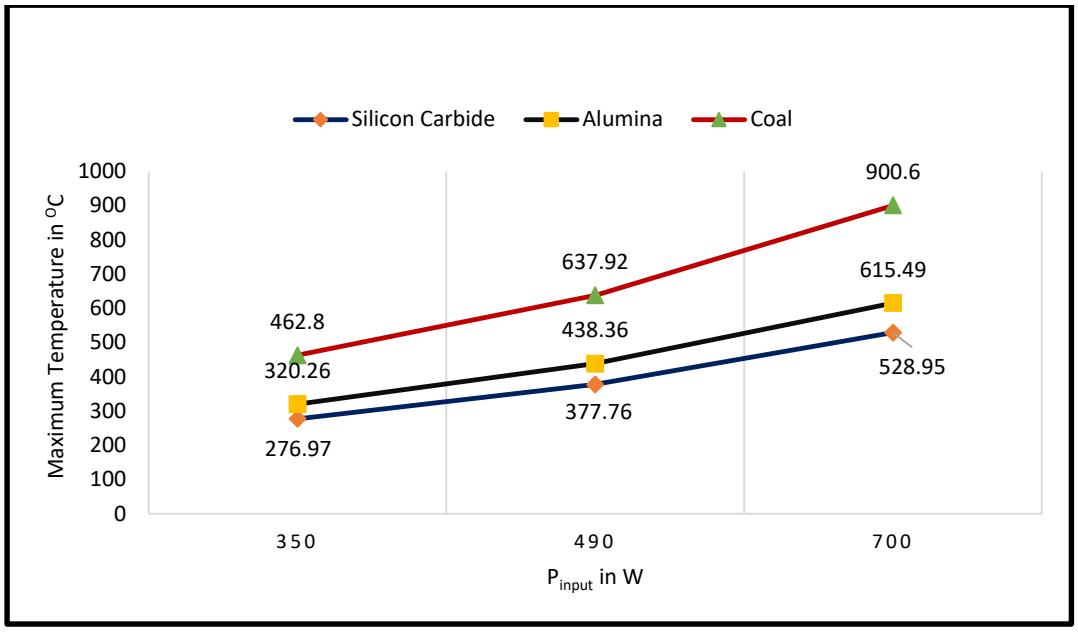


Figure 3.3. Temperature attained in (a) silicon carbide, (b) alumina, and (c) coal versus input power, P_{input} (W) and for t =300 s and h=15 mm

In terms of block location, it was discovered that the lowest position ('h' = 15 mm) was most useful for achieving high temperatures, while a power input of 700 W and a time of 300 seconds produced the highest temperatures in the susceptor blocks.

The fluctuation in electric field intensities at certain sites can be used to explain the variance in temperature at various parametric combinations in various materials. Lower losses as a result of reduced losses diminish the conversion of microwave energy to thermal energy. The regression equations (Equation 3.4, equation 3.5 and equation 3.6) developed for all the three susceptor blocks have statistically significant coefficients for the parameters and thus can be used to predict and control the temperature rise.

T_{max} for Silicon Carbide (^{O}C) = -72.7 + 0.8952 t(s) + 0.2646 P_{input} (W) - 0.610 h (mm) (3.5)

R_{square} was obtained as 79.99%

T_{max} for Alumina (^{O}C) = -145.5 + 1.2831 t(s) + 0.4082 P_{input} (W) -0.368 h (mm) (3.6)

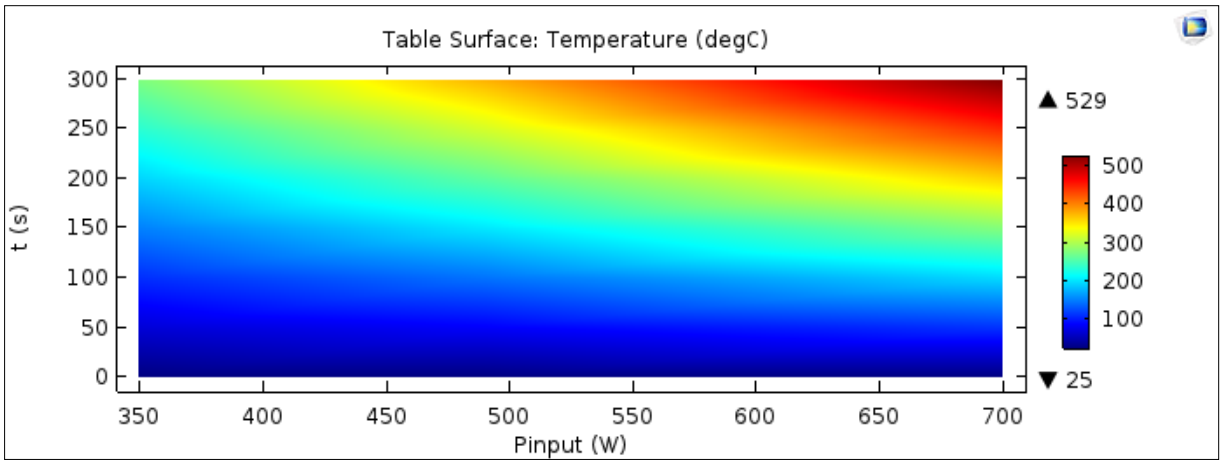
R_{square} was obtained as 92.51%.

T_{max} for Coal (^{O}C) = -36.3 + 1.434 t(s) + 0.4265 P_{input} (W) -2.564 h (mm) (3.7)

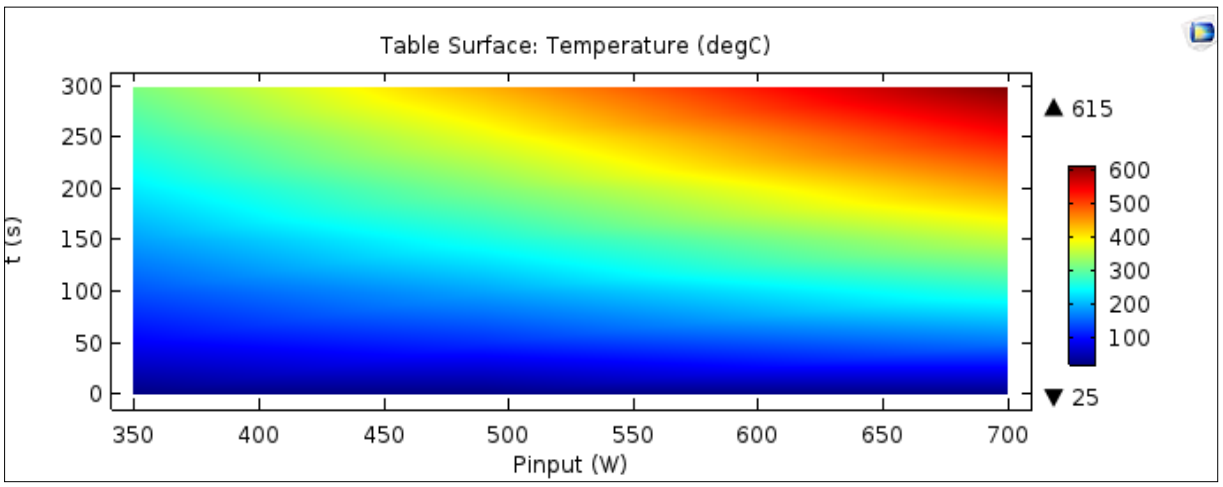
R_{square} was obtained as 83.40%.

Where 'T_{max}'(^{0}C) is the maximum temperature of the susceptor block, 'P_{input}'(W) is the input microwave power, 'h'(mm) is the position of the block from the base of the oven, 't'(s) is the irradiation time.

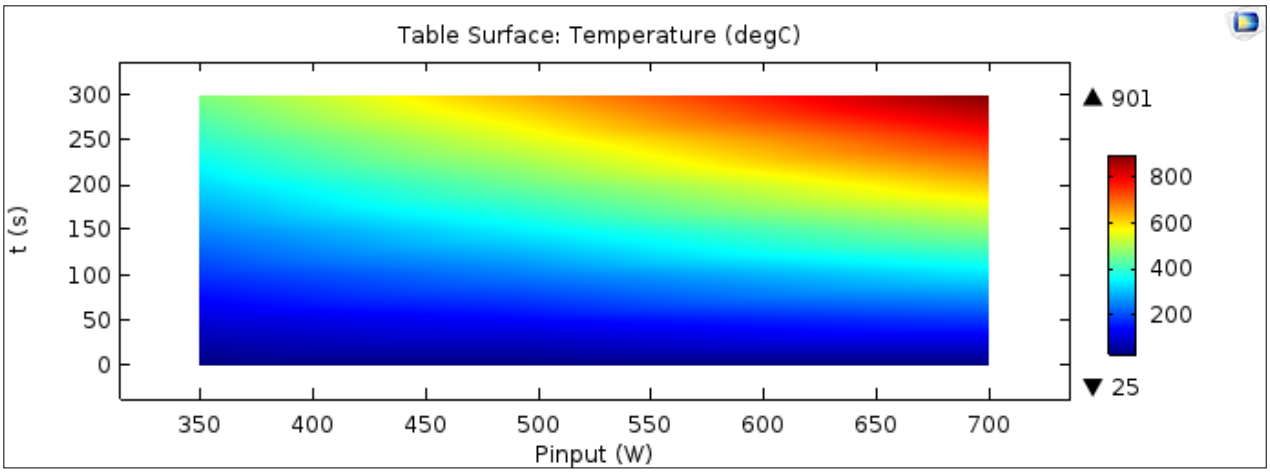
These equations would make it easier to use a specific susceptor and achieve heating at the specified rate. Contour diagrams were used to plot the parametric effects graphically (refer to Figure 3.4 a, Figure 3.4 b, and Figure 3.4 c). These graphs demonstrate how the temperature varies over time and as a function of input power in silicon carbide, alumina, and coal blocks. The effect of input power and irradiation on the highest temperature reached in these blocks is illustrated by the following three figures.



(a)



(b)



(c)

Figure 3.4. Temperature rise in (a) silicon carbide, (b) alumina, and (c) coal versus P_{input} (W) and t (s) for h =15 mm

By using the regression models, the impact of microwave input power, susceptor position, and processing time on the temperature reached by these susceptors could be understood. These models can be referred to while designing configurations for various hybrid heating applications. It can aid in addressing the issue of microwave heating in materials processing applications which are highly unpredictable.

4. Microwave-assisted Polymer Coating of Metallic Substrate

The numerical simulation was further extended to develop a set-up on curing of pure polyester coatings of steel substrate. The work was motivated from the literature review which suggested that microwave energy has seldom been used in the industrial applications of materials processing [7]. In fact, most of the microwave-assisted industrial applications are limited to the sintering process [12]. Hence, an industrial coating process was identified to explore the feasibility and to investigate the parametric effect of microwave-assisted processing. The work was carried out at "Manish Engineering Works - Aurangabad".

The existing conventional process involves conjunction of electrostatic spraying technology with furnace heating for the curing process which results in cross linking of the polymeric powder. The conventional furnace used for the curing purpose is gas fired and has its own limitation, such as loss of energy in the form of waste heat and emission concerns. On the other side, in the published literature, microwave energy has shown its effectiveness for the purpose of materials heating in

terms of energy efficiency and superior properties in processed materials [26-28]. The details of the experimental design and subsequent evaluation of coated specimens is discussed further.

4.1 Materials and Method

Cold rolled close annealed steel plate with cross-sectional dimensions 150 by 75 square millimeters, and thickness of 0.6 millimeter was used for the purpose of experiments. The chemical composition of the plate was obtained in accordance with the standard IS 513:2008 CR2(D) class, as shown in Table 4.1.

Table 4.1. Chemical composition of steel plate

Element	C	Si	Mn	P	S
% Content	0.12	0.0046	0.39	0.033	0.0087

Microwave oven with a maximum power of 700 W at a frequency of 2.45 GHz was used as an alternative to the conventional gas-fired oven for curing purposes. In Figure 4.1, the three key parameters under investigation have been highlighted.

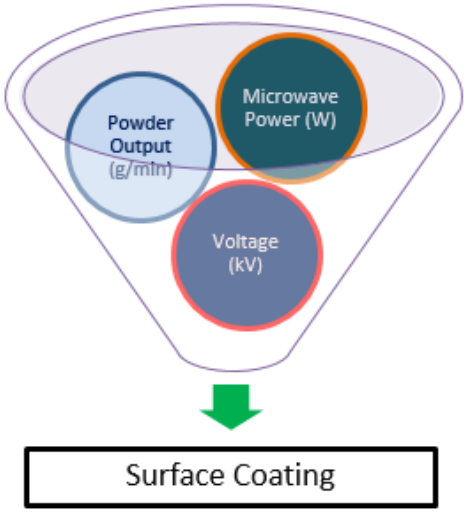


Figure 4.1. Microwave-assisted polymer coating parameters

4.2 Design of Experiments

The experimental plan was based on Taguchi L_9 orthogonal array using statistical analysis software, Minitab 17. In Taguchi analysis, the idea is to calculate signal to noise ratio. This can be used to identify the control setting that minimizes the effect of the noise on the outcomes [30]. In

the context of gloss measurement for the application chosen, the signal to noise ratio was calculated for “larger the better” condition. Table 4.2 presents nine randomized experimental combinations used for trials. Three levels of voltage, powder output and microwave power were used to design experiments. Levels of electrostatic spraying parameters were identified based on the characteristics of the machine.

Table 4.2. Parametric experimental conditions

ID	Voltage (kV)	Powder Output (g/min)	Microwave Power (W)
X1	70	100	350
Y1	70	150	490
Z1	70	200	700
X2	80	100	490
Y2	80	150	700
Z2	80	200	350
X3	90	100	700
Y3	90	150	350
Z3	90	200	490

4.3 Surface preparation

The first step was to perform pre-treatment of the substrate surface using the standard phosphate process (based on standard IS: 3618-1966) to ensure that the sample used for the tests was perfectly clean and de-rusted. Figure 4.2 shows the standard pre-surface conditioning sequence of the metal substrate.

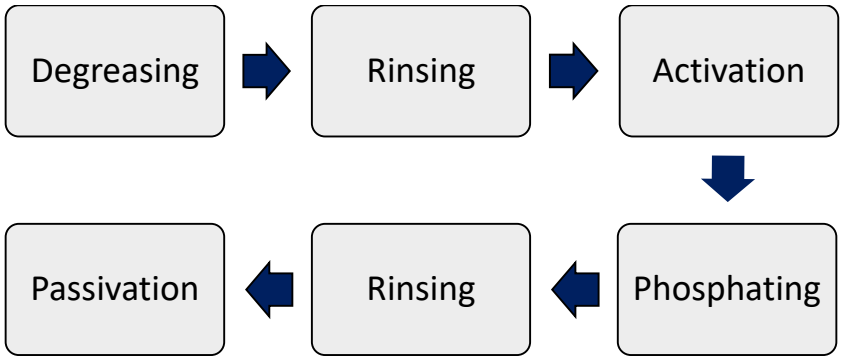


Figure 4.2. Surface preparation before powder coating [31]

4.4 Electrostatic Spraying

The surface treated samples were then sprayed with the pure polyester powder obtained from M/s Marpol Pvt. Ltd. The parameters of the machine were set in accordance with the experimental plan. In Figure 4.3 the schematic of electrostatic powder spraying is shown.

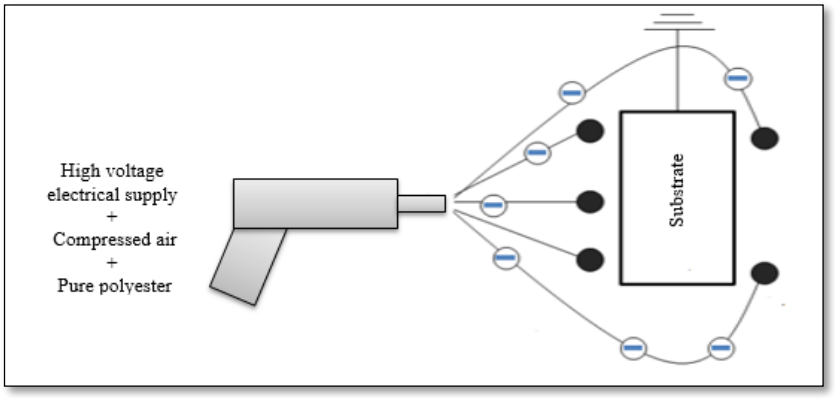


Figure 4.3. Electrostatic spraying mechanism [32]

The spray gun is supplied with compressed air and polymeric powder for coating the cold rolled steel substrate. This substrate is grounded electrically. The powder from the spray gun is transported to the substrate using compressed air. Subsequently, the electrostatic attraction force allows the powder to cling to the substrate. The inlet air pressure and the fluidized air pressure required to ensure flow-ability of coating powder were kept constant at 3 kg/cm^2 and 1 kg/cm^2, respectively. Once powder was sprayed on the substrate, the combination was transferred to a microwave oven for the curing process.

4.5 Microwave Curing

Microwave curing of the specimens sprayed with the pure polyester powder was carried out using an indirect microwave heating method termed as “microwave hybrid heating” using the susceptor [33,34]. The reason is the inability of the metals and the powder to directly interact with microwaves. Microwave oven of 700 W power rating was used for the process.

A slot was prepared in the 40% refractory brick of alumina to hold the cold-rolled steel substrate. To derive the heat needed for treatment, a susceptor was required. Susceptors are the materials that convert microwave radiation to thermal energy [35]. A numerical simulation was done to select a suitable susceptor for the process. The aim was to control the temperature rise to an order of

200 ^{0}C, as an excessive increase in temperature could lead to the degradation of the coating powder. After studying materials such as silicon carbide, charcoal and graphite using numerical simulation, it was observed that graphite showed the desired temperature rise characteristics.

As a result, the metal substrate was placed under graphite sheet that also prevented direct exposure to microwave radiation. Figure 4.4 shows the experimental arrangement's schematic view.

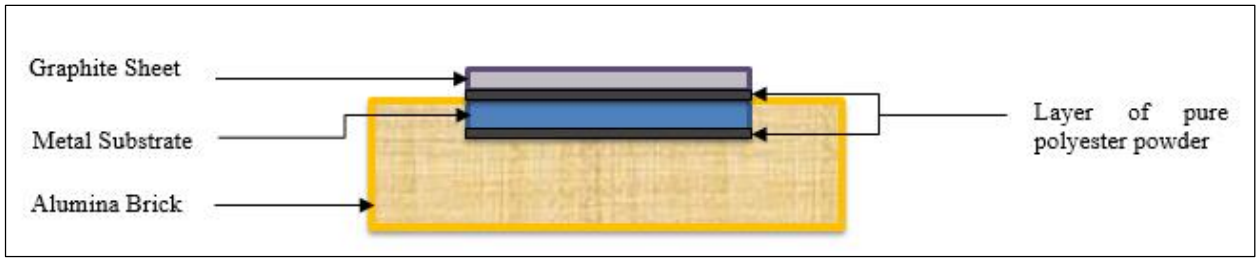


Figure 4.4 Set-up for microwave heating

The plate, pure polyester powder, and graphite susceptor sheet were placed together in the microwave cavity, as shown in Figure 4.4. The insulation brick of alumina was machined to prepare the slot for the substrate, as shown in Figure 4.5 a. The plate was sprayed with the coating powder (refer to Figure 4.5 b) using electrostatic gun as per parametric combinations shown in Table 4.2.

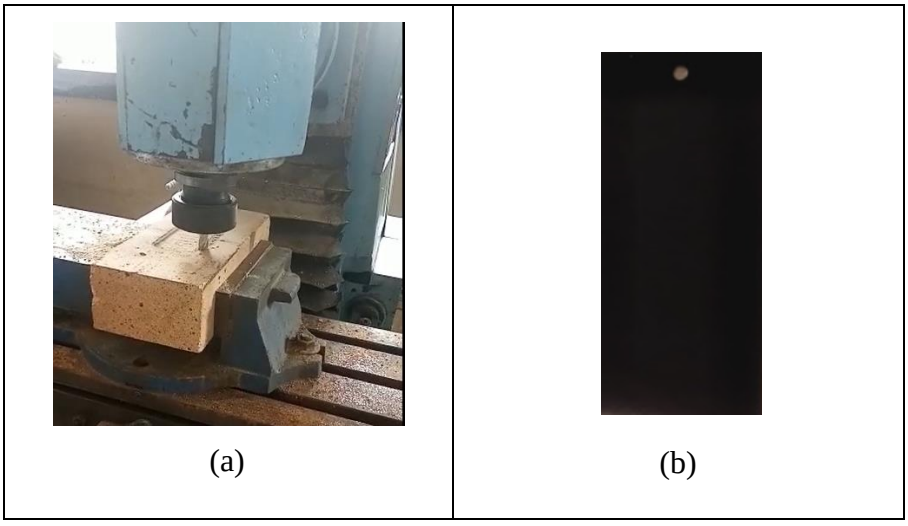
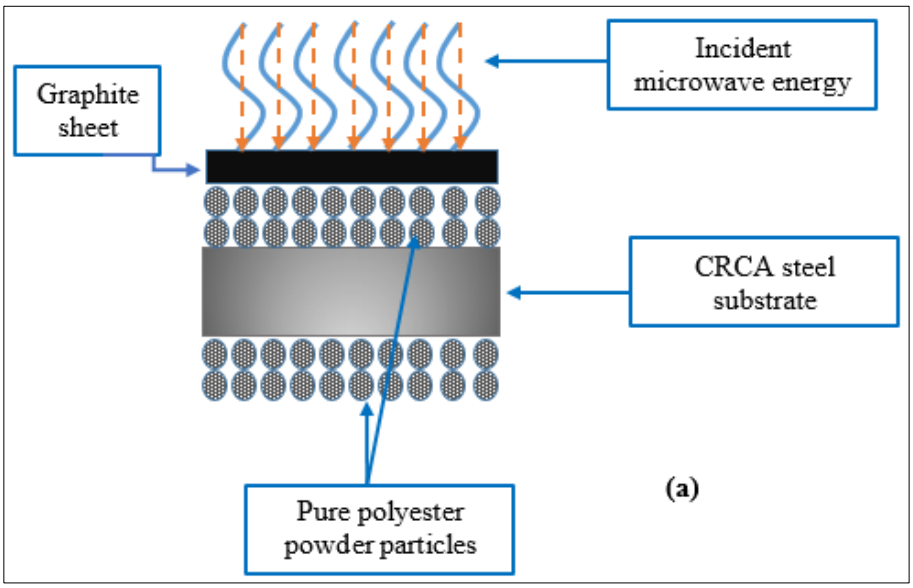
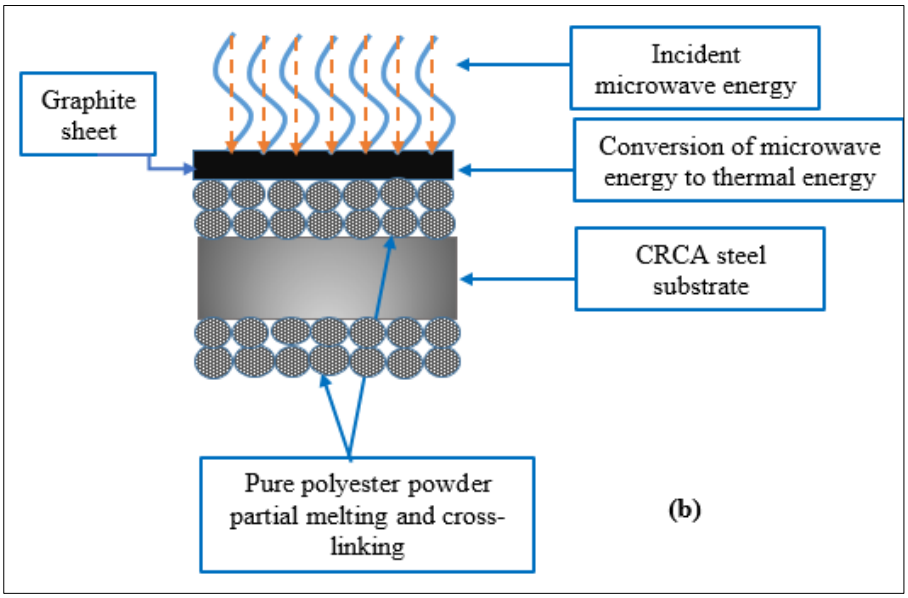


Figure 4.5 a. Insulation brick slot preparation, 4.5 b. Substrate post-sprayed powder (uncured)

Microwave power was varied for the preparation of different samples based on the factor combination of Taguchi orthogonal array. The time of irradiation was fixed to 10 minutes optimized based on initial trial experiments. The mechanism of microwave curing is presented in

Figure 4.6. The incident microwave radiation interacts with graphite and generates heat. The extent of transformation is a result of material property discussed in the literature review section. This heat is transferred to the polymeric powder which then gets cured in the form of coated layer.





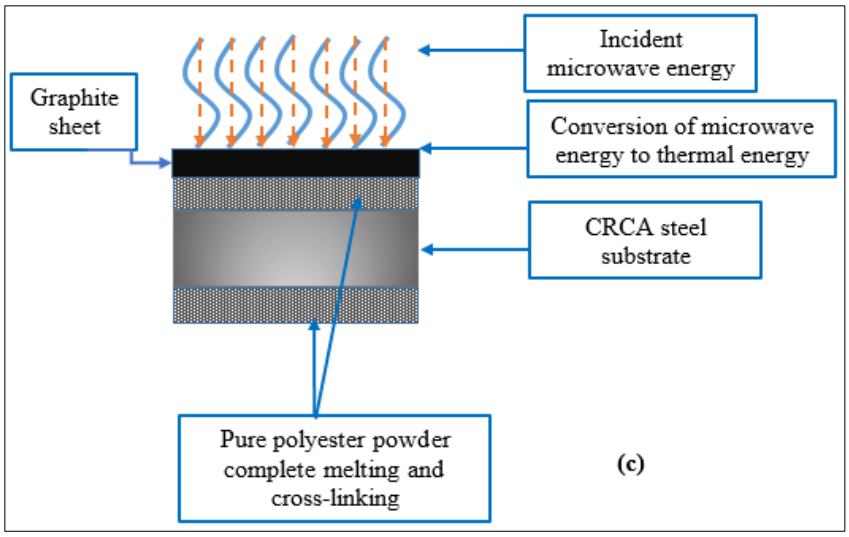


Figure 4.6 Mechanism for curing: a) Incident microwaves on graphite susceptor, b) transformation of electromagnetic energy into thermal energy and partial melting of polymeric powder, c) complete curing of polymeric powder

4.6 Summary of Outcomes

In order to evaluate the applicability of microwave energy in the industrial coating process, the specimens prepared by microwave-assisted processing were assessed for dry film thickness (DFT), gloss, impact strength and corrosion resistance. The outcomes of these measurements taken for the specimens prepared using nine randomized factorial combinations have been presented in the subsequent sections.

4.6.1 Dry film thickness (DFT) Measurement

DFT is a prominent characteristic of a polymer-coated specimen. It is measured as the thickness of the coated layer after the curing has occurred. The coating developed in the present work required its DFT to be around 60 microns as per the specifications. The coating thickness was measured for all the specimens using “Coatmeasure”, a coating thickness measurement gauge. This instrument is calibrated using standard thickness shim and then used for the coated specimens [36]. The value of DFT for the specimens was found to be in the desired range of 60 ± 5 microns.

4.6.2 Gloss measurement

The specimens obtained after each of the nine experimental trials were measured for “Gloss units (GU)” based on the ASTM D523 standard. Gloss rating is obtained by comparing the specular

reflectance from the specimen and that from a black glass standard. This specular reflectance also depends on the refractive index of the specimen surface, hence there is a change in the gloss ratings as the surface refractive index changes [31].

A direct measuring instrument known as a "Glossmeter" was used to obtain the values of gloss. Five values of gloss were acquired at different locations on the coated specimen and its mean was recorded. Table 4.3 shows the gloss units and corresponding signal to noise ratio for each factorial combination.

Table 4.3. Response table for parametric combinations

Specimen Designation	Input parameters			Response parameter	
	Voltage (kV)	Powder Output (g/min.)	Microwave Power (W)	Gloss (%)	Signal to Noise Ratio
X1	70	100	350	52.3	34.3700
Y1	70	150	490	64.1	36.1372
Z1	70	200	700	62.6	35.9315
X2	80	100	490	63.3	36.0253
Y2	80	150	700	60.8	35.6781
Z2	80	200	350	52.4	34.3866
X3	90	100	700	73.2	37.2902
Y3	90	150	350	56.6	35.0563
Z3	90	200	490	60.6	35.6495

Figure 4.7 shows the coated surfaces for the nine factorial combinations. Images of X1, Z2 and Y3 specimens reveal low quality textured surfaces which is also verified by the lower gloss units corresponding to these specimens. On the other hand, specimens, Y1, Z1, X2, Y2, X3 and Z3 showcase relatively shinier appearance. The gloss values are found to be higher for combinations involving either high power input or lower powder output from the spray gun which ensured maximize energy density for melting and effective curing of pure polyester powder.

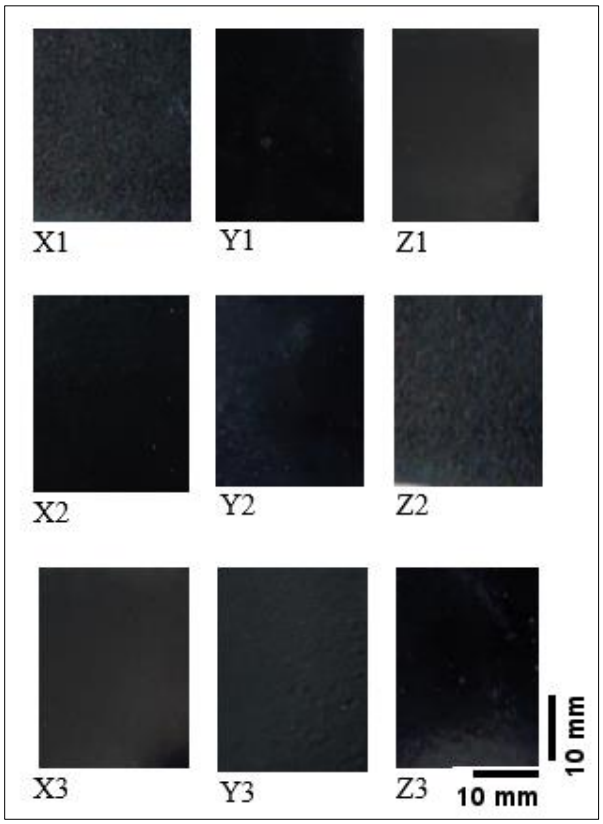


Figure 4.7 Powder coated specimens

The factorial combinations involving the least magnitude of microwave power were observed to have the gloss unit on the lower side. In fact, these values were below the specification limits, that is, (60-90) GU. It can be attributed to insufficient thermal energy conversion leading to incomplete curing of the polymeric powder. Similarly, the gloss value was found to be on the lower side as the powder output from the spray gun was increased. This could be due to the reduced density of thermal energy for the complete melting of the polymeric powder layer.

Furthermore, on the analysis of the values of "signal to noise (SN)" ratio for different factorial combinations, the maximum SN ratio was obtained for the voltage of 90 kV, powder output 100 g/min and power input 700 W. It is also evident through the main effects plot for SN ratios, (refer to Figure 4.8).

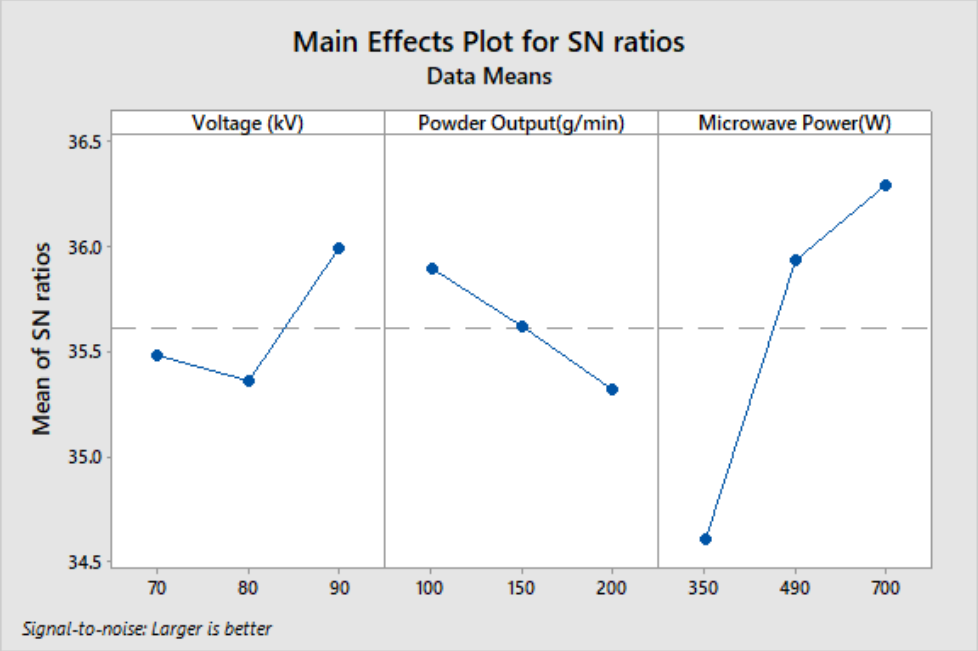


Figure 4.8 Main effect plots for SN ratios

To understand the impact of each of these factors, “Delta” values were determined for all three These delta values are calculated by subtracting the maximum and minimum values of the SN ratio corresponding to each factor. The factor resulting in the maximum difference is ranked one. It was revealed that microwave power is the most significant causal factor while voltage and power output were ranked second and third respectively.

4.6.3 Impact Testing

The specimens were also tested for impact strength using a DuPont impact tester. Through this equipment, the impact endurance of the coated specimen is tested. The purpose is to check if the specimens under test can withstand the effect of falling weights from a certain height. Drop weight of 2.25 kg was dropped from a height of 62 cm as per the specifications of automobile OEM. Barring the “X1” specimen, no cracking, flaking, or any other sort of damage was observed on the concave surface. Thus, it validated the fact that curing has been satisfactorily achieved for eight out of nine specimens. The failure under impact in the first specimen can be attributed to under-heating during the curing process owing to low power input.

4.6.4 Corrosion Testing

Corrosion resistance is crucial for any automobile component due to its usage in harsh environments and thus a vital functional requirement. Therefore, a corrosion test was performed as per ASTM B117. The test was carried out at 35 $\pm$ 1 ^{o}C with 5% NaCl in DM water. Figure 4.9 a and 4.9 b reveal the rust conditions of two specimens identified as Z1 and Z2 respectively.

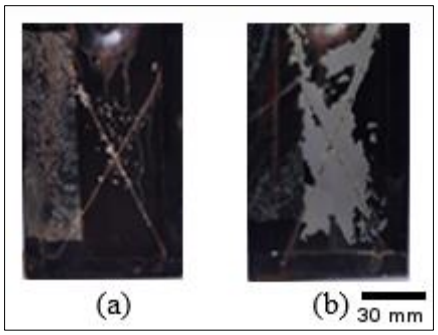


Figure 4.9 Corrosion tested specimens: a) Z1, b) Z2

Rust creepage for both the specimens was observed to be 3 - 4 mm and 6 -10 mm respectively after 240 hours. Localized blistering occurred for Z2 which was processed at low power input (350 W) while specimen Z1 didn't show any profound blistering. Z1 was processed at maximum power input of 700 W. It validated the significance of large power density leading to efficient heating and superior coating quality. Other specimens also demonstrated rusting after 240 hours.

5. Development of Device for Joining Metals using Microwave Energy

After an illustration of microwave-assisted industrial coating process, the research work was extended to develop a customized device for the purpose of material joining using microwave energy which is another application area with an extensive potential for research. A comprehensive review of methods discussed in the microwave joining literature [35, 36], following conclusions were drawn:

1. There is no mechanism in a domestic oven to monitor and keep a check on the temperature rise during the heating in the joint area.
2. Charcoal, has been used as a susceptor in most of these experiments, which burns out during the process. This in turn affects the subsequent heating rate.

3. The arrangement inside the domestic oven cavity for the joining purpose is temporary, this minimizes the reliability of the joining process.
4. The atmosphere around the joining area to avoid cross contamination of the joints is not controlled.
5. The provision for clamping the base plates (to be joined) was missing.

Apart from the above observations, it was also identified that existing domestic microwave ovens cannot be used for prolonged periods of operations. In addition, controlling the process parameters is of paramount importance while performing the joining of materials. These ovens also lack provision for automatic control over process parameters.

Since, the idea of using microwaves for joining is new and requires knowledge on conversion of microwave energy into thermal energy and in the absence of a dedicated device, it is exceedingly difficult to perform process. It was realized that it is important to develop a device to overcome the limitations of previous work and to improve control over the connection of microwave energy materials. Challenge in using earlier demonstrations on joining using microwaves were the limitations related to controlling temperature rise, environment in the joining zone, lack of clamping, efficient conversion of electromagnetic energy to thermal energy, etc. This was possible with the help of a dedicated device which can be developed further to be used in industrial application.

5.1 Preliminary Design: Joining Device

In any microwave energy device, certain components are mandatory. The device components were identified as follows:

- Microwave source: Microwave devices used for thermal energy applications such as domestic oven is a high power equipment and the microwave source typically used in such applications is magnetron. The electric potential applied across the magnetron combined with the magnetic field existing around the magnetron due to inherent magnets results in generation of electromagnetic radiation in the form of microwaves. The frequency of microwaves used for thermal application is limited to certain values to avoid interference with the microwaves used in telecommunication. The value is typically 2.45 GHz.

- Waveguide: This is an equally crucial element of any microwave system as it channelizes microwave energy to the desired space or location. The significant function of waveguide material is to be an excellent reflector of microwaves. The dimensions of waveguides should be such that all the microwaves move forward rather than reversing back to the source.
- Microwave cavity: It is also called as resonant cavity for the very reason that its dimensions should be such that it can accommodate the microwave within. Conventional domestic ovens have a box like cavity, another geometry used, albeit sparsely is a cylindrical one. An alternative to such cavities is the use of waveguide itself for positioning and processing the materials. However, the size of the waveguides limits the positioning and quantity of materials to be processed.
- Susceptor: This becomes a mandatory component for any microwave device which is to be used for processing metals. The primary reason being, direct exposure of microwaves onto a metallic specimen generates spark due to accumulation of charges around the edges of the metal body. Secondly, the penetration depth in case of metals is also of the order of microns which limits the transformation of microwave energy to thermal energy. Hence, it is imperative to use a strategy of indirect heating which requires use of susceptors. As discussed in earlier chapters, susceptors interact with microwaves readily and transform the electromagnetic energy to thermal energy through various loss mechanisms discussed in literature review chapter.
- Insulator: The heat resulted from the interaction of susceptor with microwaves can lead to extremely elevated temperatures (of the order 1200 ^{o}C -1500 ^{o}C) which can cause damage to the electronic circuits and electrical devices such as transformer and cables along with magnetron and body of the device. Hence it is imperative to provide an insulator to avoid transfer of heat to the undesired regions of the device.
- Clamping and positioning mechanism: The metal plates to be joined must be positioned in the vicinity of the susceptor to maximize transfer of heat. At the same time, a clamping mechanism is needed to hold the plates at the desired location and ensure sufficient clamping pressure between the two plates to achieve effective joining.
- Temperature measurement and control: This is critical to any materials processing application involving heat. Be it hot working processes, machining processes, casting processes, sintering in powder metallurgy or welding/joining processes. It is important to choose a suitable

temperature measurement sensor and a controller to switch off the microwave power after desired temperature is achieved.

After identifying the components required for building the set up in the preliminary design phase. The subsequent step was to identify the specifications of each of these elements of the device and to select/build the components as per the requirements. Subsequent section presents the details of the device design.

5.2 Detailed Design: Joining Device

The joining enclosure is made from mild steel angles with a mica sheet at the base to avoid heat loss through the base of the plates to be joined. Only the joint interface is exposed to heat radiated from susceptor block. Both the plates to be joined can be clamped using a screw mechanism. The susceptor block is surrounded by alumina insulation compound which is placed inside a resonant cylindrical cavity. The microwaves interact with the susceptor resulting in conversion of electromagnetic energy to thermal energy.

The thermal energy is transferred to the joint interfaces thereby melting the interfacing powder/ joint interfaces. This leads to in-situ joining of the plates. The joining zone is enclosed in an insulated environment to avoid thermal losses. The temperature sensor is positioned at the interface and an opening inert gas is provided to control the ambient conditions.

The device has the following benefits.

1. Fixture for fixing plates to be joined.
2. Temperature measurement system and control over the temperature rise.
3. Provision for controlling atmosphere within the joining area.
4. It can be used to join several types of materials.
5. The device is compact, portable and user friendly.
6. It supports the concept of green manufacturing.

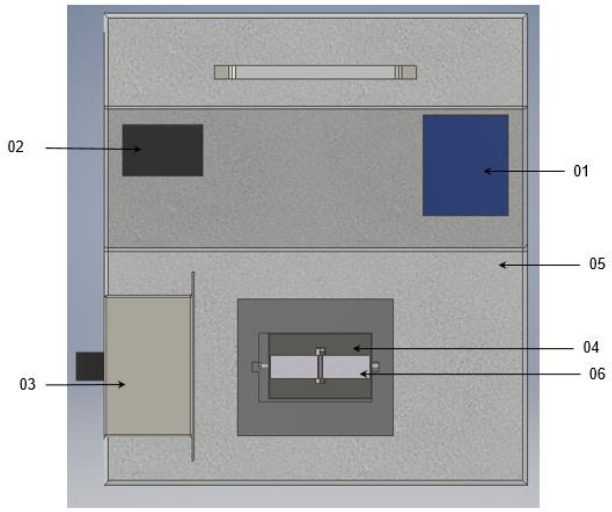


Figure 5.1 Top view of the customized joining device

The objectives and features noted above are described in detail using the drawings in which the reference numeric values represent the elements of the device. Figure 5.1 is the top view of the device. While Figure 5.2 is the sectional front view of the device. In the drawings, the numbers correspond to the main elements of the device. The details are as follows: 01. Control Panel; 02. Temperature Display; 03. Cover; 04. Joining slot; 05. Metal housing; 06. Plates to be joined; 07. Screw mechanism; 08. Susceptor block; 09. Alumina Insulation; 10. Insulation brick;11. Cylindrical cavity; 12. Transformer; 13. Capacitor; 14. Magnetron; 15. Waveguide

Figure 5.1 shows the ergonomically positioned control panel (01) with a provision to set the duration, power levels (1-10) where '10' represents 100 % of maximum power which is equal to 1000 W and '1' represents 10 % of maximum power that is 100 W. This allows for suitable selection of power magnitude which results in control over the temperature rise.

While (02) is the digital display used to show the temperature at the interface of the plates to be joined. It can also be used to set the set value of temperature to control the temperature rise. The control over temperature is done using PID controller. It enhances control over the temperature rise.

The joining zone is part of a modular set-up covered and isolated from the atmosphere with the help of cover (03). The cover provided with a handle is made up of mild steel of 5 mm thickness. A thin mica sheet is provided at the bottom side of this modular set-up to minimize heat loss from the plates to be joined.

This modular set-up consists of a slot (04) of size 102 mm × 30 mm enclosed using mild steel angles from the four sides. This is mounted over the metal housing (05) which carries the whole assembly of elements which are part of the device. The plates to be joined are represented by (06), which are clamped in the modular setup.

Internal construction of the device is presented in in Figure 5.2 showing the sectional front view shown. Material plates (06) are fixed within the joining zone using an M10 size bolts which is part of screw mechanism (07) that provides the clamping force. This allows for constraining the movement of plates to be joined during melting at the interface.

The heat required at the joining interfaces to melt the slurry of metal powder and epoxy resin is received from the silicon carbide and zirconia based susceptor block (08). This block converts microwave energy to thermal energy. To avoid heat loss in the cavity area, alumina-based insulation, which is transparent to microwaves but captures thermal energy, is used. This thermal energy is directly to the interface of the metal plate 06. To avoid the loss of thermal energy from the top side of the metal plate, the insulation brick, shown as 10, is used on the top of the connection slot. Insulation (09) is housed in a cylindrical resonant (11) cavity suitable for microwave transmission without being reflected in the source. The size of the resonant cavity is crucial for maximizing the transmission of microwave energy to the receptor. Transformer (12) and the capacitor (13) are the two key components of power supply system and critical to generation of microwaves through magnetron. Due to the high voltage involved in the operation of the magnetron, a slight looseness in the connection can lead to the non-powering of the magnetron. Voltage applied to across the magnetron (14) results in the generation of microwaves at 2.45 ± 0.05 Gigahertz. The microwaves are transmitted through the WR 340 waveguide (15). The selection of the appropriate waveguide governs the accurate transmission of microwaves from the magnetron antenna.

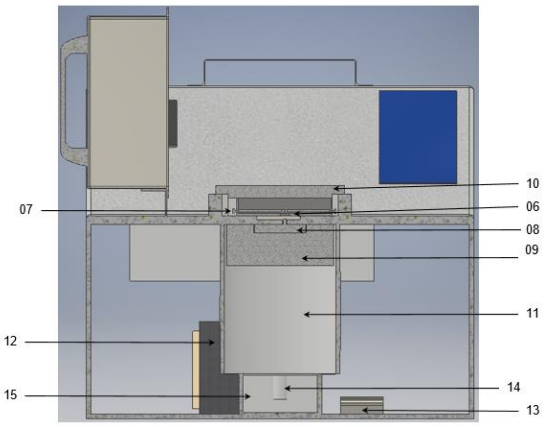


Figure 5.2 Sectional front view of the customized joining device

5.3 Summary

The device for joining of materials utilizing microwave energy was designed and built to leverage the use of microwave energy. It can be utilized for other industrial applications as well wherever thermal energy is required. The device generates the heat required to carry out melting at the joint interface using susceptor-assisted energy conversion. The joining zone is strategically positioned to get exposed to the heat generated inside the susceptor made up of silicon carbide and zirconia-based material combination. In addition, exceptional care has been taken to avoid heat losses around the joining zone to maximize energy efficiency and minimize the process time. The system consists of a temperature monitoring and PID controller system to keep a check on temperature rise during the joining process or similar microwave heating application thereof. It also comprises of a provision to clamp the plates to be joined within a joining zone using screw mechanism and purging of inert gases to avoid contamination of the joint area. This device provides increased control over the microwave joining process and can be benchmarked to develop other devices for thermal energy-based applications using microwave energy leading to green manufacturing.

6. Microwave-assisted joining of non-ferrous materials

After the development of the device for joining using microwave energy, joining trials have been carried out. It was identified that in the published literature, the joining experiments have been mostly carried out with with materials having relatively higher melting point (>800 ^{o}C) and lower tendency of oxidation [7]. The joining of aluminium based alloys using microwave energy is still an area that can be investigated at a larger scale. The key challenge in utilizing microwave energy with a material like aluminum is its poor interaction and high microwave reflectivity due to high

electrical conductivity. Aluminium alloy is one of the most widely used materials in automotive and aerospace industry. Its processing is critical to performance of these industries.

6.1 Experimental Description

In the literature pertaining to microwave joining published in the recent years, conventional microwave oven has been used for attaining the fusion point of the filler material. These ovens have obvious limitations as the joining set-up is prepared temporarily with very little control over the heating process. Hence, as a part of the joining research, a dedicated apparatus was developed (patent filed) to establish better control over the heating process (refer to section 6). Schematic diagram of the joining zone is shown in Figure 6.1. The plates to be joined are placed inside a housing comprising of a screw arrangement for clamping the plates, a mica sheet below the plates to keep them insulated from the heat avoiding thermal distortion, susceptor to convert electromagnetic energy into thermal form, an insulator cover to trap the heat inside the joining arrangement. This system allows for better control over the process over the ones presented in the literature as the set-up is customized for specifically joining purpose and comprises of a permanent fixture to hold the plates to be joined.

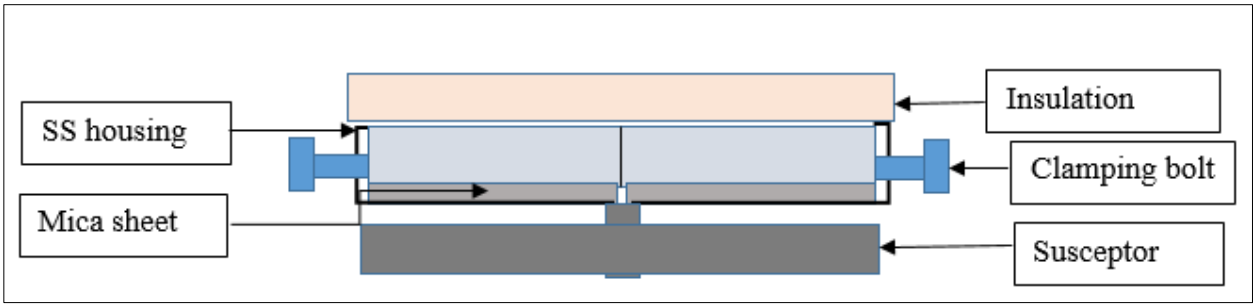


Figure 6.1 Joining arrangement

In this work, joints of AA6061 and other aluminum alloys such as AA6063 and AA3003 were prepared inside a customized microwave heating device to check the feasibility and to characterized the joints prepared using this green processing technique. Filler powder was chosen to be AA4043 powder of size 45 microns. The presence of silicon in the powder provides significant fluidity to the filler.

The plates to be joined were cleaned thoroughly using a commercially available aluminum cleaner to remove the oxide layer and any contaminants over the joining surface. In addition, the surface to be fused was polished and ground using emery paper. The filler powder (AA4043) is mixed with a Blumer epoxy resin to prepare a slurry mix. A filler epoxy ratio of 70:30 was obtained after

initial trials and then used to prepare the slurry mix. This slurry mixture was used to fill the gap of 1 mm size between the two joining plates. The experimental summary is given in Table 6.1.

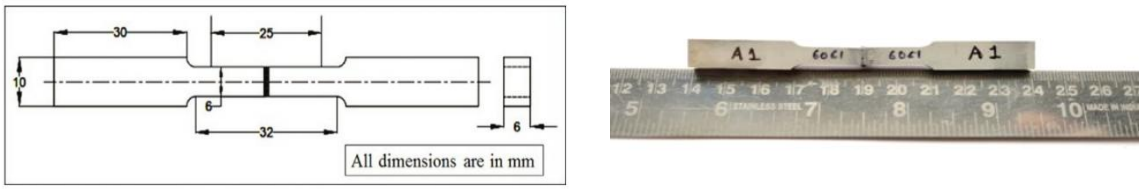
Table 6.1 Details of the Joining Experiments

Particulars	Specifications
Fusion region c/section	6 mm × 5 mm
Filler powder	AA4043
Epoxy resin	Blumer 1450XX
Time of irradiation	720 seconds
Microwave Power	1000 W

6.2 Testing and Characterization of joints

6.2.1 Mechanical testing

The joint specimen was prepared as per ASTM E8/E8M as shown in Figure 6.2a and 2b.



(a) (b)

Figure 6.2: a) Tensile test specimen as per ASTM E8/E8/M, b) Sample tensile test specimen

Tensile strength of the joint was determined. It can be seen from the load versus deflection plot for the joint (Figure 6.3) that there is negligible plastic deformation which indicates that the joint failure is of brittle nature. The ultimate tensile strength of the joint was obtained as 5.473 MPa which corresponded to the load of 163 N.

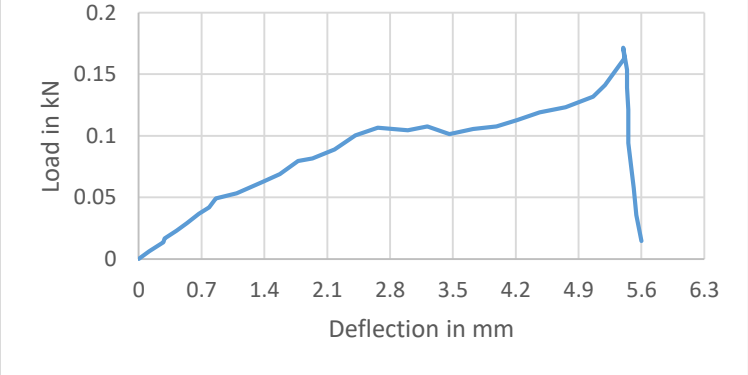


Figure 6.3 Load versus deflection plot for AA6061-AA6061 joint specimen

The specimens were subsequently investigated for micro-hardness across the zones to check the effect of joining process on the base metal and the fusion zone. Indents were made at an equal interval of 1 mm across the specimen. It can be seen that the micro-hardness was found to be higher

in the fusion zone (refer to Figure 6.4). Vickers micro-hardness tester- Mitutoyo HM 200 was used for the purpose. Load of 0.3 kgf was applied for indentation.

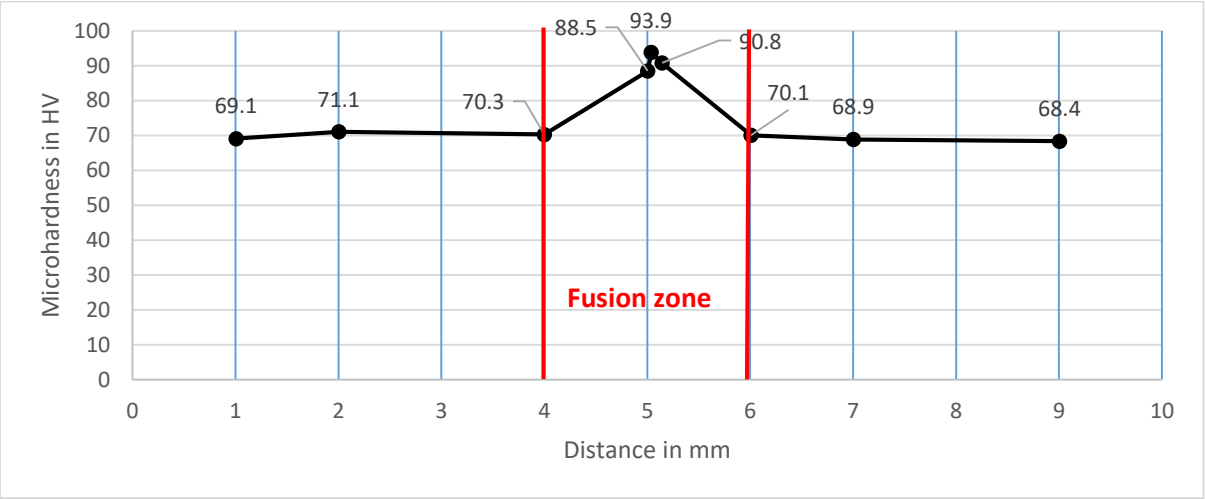


Figure 6.4 Microhardness of the AA6061-AA6061 Joints

It can be observed that there is drastic rise in the micro-hardness at the fusion zone which is 20 HV greater than the micro-hardness of the base plates. Subsequent, XRD analysis was carried out to deduce the cause of high hardness in the fusion zone.

6.2.2 X-Ray Diffraction (XRD) Analysis

The joint specimen was analyzed using X-Ray Diffraction (XRD) technique (refer to Figure 6.5) to capture the formation of inter-metallic compounds that would have led to poor joint strength and high magnitude of micro-hardness.

The analysis revealed that there is formation of several intermetallic compounds such as Al-Fe-Si, Al-Mg, Al-Si, Al-Fe along with aluminum oxide which have detrimental effect on the strength of the joint due to the inhomogeneity of the fusion zone. Moreover, high intensity of these phases suggest that these were formed after getting exposed to high amount of thermal energy received in a short period of time and remained insoluble in the fusion matrix which explains the reason for poor joint strength and high hardness of the joint area.

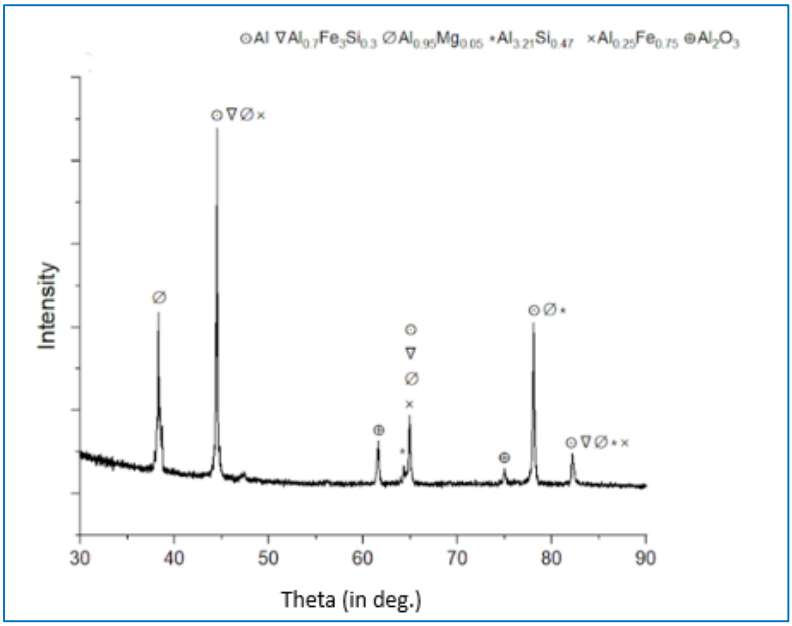


Figure 6.5 XRD analysis of the microwave-processed AA6061-AA6061 Joints

6.2.3 Scanning Electron Microscopy (SEM)

The processed joints were characterized using SEM. It was revealed that there is lack of fusion at the interface between the parent metal and the filler. This could be attributed to oxidation of aluminum at the interface. SEM micrographs for other joint specimens revealed similar characteristics.

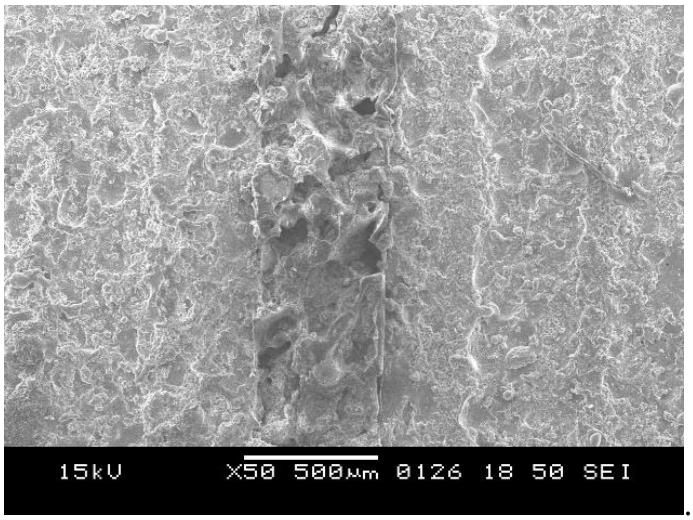


Figure 6.6 SEM of AA6061-AA6061 Joints

7. Conclusion and Future Scope

Based on the literature review, numerical simulation, experimental studies on coating, development of joining device based on microwave energy and subsequent joining experiments, following conclusions have been drawn. Future scope of the research is also stated thereafter.

7.1 Conclusion: Numerical Analysis of Susceptor Heating

- The comparative analysis of the susceptor materials, viz. coal, alumina and silicon carbide showed that interaction of susceptor material with the electric field component is the major contributor towards temperature rise. Hence, along with the dielectric properties, identification of spatial distribution of electric field intensity with the help of numerical simulation is critical for the optimal positioning of the material to be heated.
- The results also indicated that the apart from dielectric properties, temperature distribution is significantly affected by the thermal conductivity of the material being subjected to microwave irradiation. Although coal acquired maximum temperature of 901 ^{o}C which was found to be highest amongst the susceptors chosen, that is, alumina and silicon carbide, its temperature field under microwave irradiation is non-uniform. Hence, a susceptor with poor thermal conductivity is unsuitable for the use in microwave heating applications.
- Regression models for the maximum temperature rise in the three susceptor materials were found to be statistically significant. Thus, it could be stated that the input parameters; microwave power, time of irradiation and position of the susceptor block have significant influence on the response parameter; maximum temperature.

7.2 Conclusion: Polymer Coating of Metallic Substrate

- Taguchi analysis of the powder coating process revealed that the applied voltage in the chosen range {70 kV, 80 kV, 90 kV} and the powder output from the gun having levels {100 g/min., 150 g/min., 200 g/ min.} have significantly lower impact on the gloss units. While microwave power {350 W, 490 W, 700 W} has the most significant impact on the gloss unit of the coated specimens. Maximum signal to noise ratio was obtained corresponding to a factorial combination of maxmum power of 700 W, applied voltage of 90 kV and spray gun output of 100 g/min. This can be attributed to optimum availability of thermal energy for the coating process.

- Mechanical properties such as impact strength was found to be satisfactory for all the specimens according to the specified standard ASTM D2794 (except the one corresponding to the factorial combination of 70 kV, 100 g/min., 350 W). No visual evidence of cracking, flaking or any other sort of damage was observed for the coated specimens. This illustrates that microwave curing led to good adhesion of the polymer with the substrate. This can be attributed to the uniform transfer of thermal energy from graphite susceptor to the whole surface providing rapid and efficient curing.
- Corrosion tests of the specimens using the salt spray test standard ASTM B117 resulted in rust creepage after 240 hours. The results were encouraging and provides scope for further improvement in the hours of exposure before corrosion failure. It was inferred that with a closer control over the microwave curing process and an integrated spraying and microwave curing system can lead to increase in the duration until corrosion failure.
- This environment friendly coating process demonstrated that with the use of microwave energy there is saving in curing time from 30 minutes to 10 minutes.

7.3 Conclusion: Device for Joining and Joining Experiments

- A customized heating device based on microwave energy for carrying out joining experiments was built (a patent has been filed and published). It included selection of important constituents such as microwave generator, microwave transmission line (waveguide), insulators to protect the internal circuitry, temperature sensor and susceptor which is critical to the applications involving metal processing.
- Joining of non-ferrous metallic plates was successfully carried out within the customized device. However, while joining aluminium alloy combinations, the tensile strength obtained for the joints was found to be low, In addition, results of microhardness testing showed sharp rise in the hardness values at the fusion zone, which concludes that filler morphology and the methodology used for preparing the slurry using eopxy resin has a detrimental effect on the mechanical properties of the joint.
- X-ray diffraction (XRD) and scanning electron microscopy (SEM) studies were carrried out on the joint specimens. It indicated formation of aluminium oxide at the plate interfaces and inter-metallic compounds (Al-Fe, Al-Fe-Si) within the fusion zone. SEM images also

showed complete melting of the filler powder in the fusion zone. Lack of sufficient diffusion of the filler at the interface corroborates the reason for lower strength of the joints.

- Filler with an alternate morphology was tested for joining copper plates inside the customized joining device. A commercially available solder paste was used as a filler. The joint strength was increased with negligible porosity as seen in the micrograph. This indicates that the use of epoxy resin to prepare slurry is a major cause of poor strength found in the joints of aluminium alloys.
- Another key finding in the joining experiment based on microwave energy is that a very small heat-affected zone is formed in all the material combinations joined. This is an important observation as the concentration of thermal energy derived from microwave irradiation can be focused only at the fusion zone. This prevents thermal distortion which is generally associated with the existing joining processes. Thus, with the availability of suitable combination of filler paste and materials to be joined, sound fusion joints can be prepared using the customized device.

7.4 Future Scope

- Numerical simulation can be extended to evaluate processing of different material combinations for applications such as cladding, joining and casting of materials.
- For large-scale polymer coating application, a dedicated microwave energy based furnace can be designed and integrated with the electrostatic spraying process to prevent powder loss, ingress of moisture and contaminants.
- Specific studies to determine energy advantage of microwave-assisted processing applications can be carried out.
- In joining applications, there is wide potential for exploring joining of materials with right selection of fillers and their form. This would facilitate joints of higher strength.

8. Publications

1. Loharkar, P.K., Ingle, A. and Jhavar, S., 2019. Parametric review of microwave-based materials processing and its applications. *Journal of Materials Research and Technology*, *8*(3), pp.3306-3326. **SCI-E/Scopus indexed**.

2. Loharkar, P.K. and Ingle, A., 2021. Assessment of microwave susceptors for optimum temperature rise using parametric numerical simulation. *Journal of Thermal Engineering*, *8*(3), pp.323-334. **ESCI/Scopus indexed.**
3. Loharkar, P.K. and Ingle, A., 2023. Evaluation of characteristics for microwave-assisted polymer coating of the steel substrate. *International Journal of Materials Research*, Published online by De Gruyter, April 6, 2023. **SCI-E/Scopus indexed.**
4. Loharkar, P.K. and Ingle, A., 2020, March. Numerical analysis of microwave heating: Fundamentals and applications. In *IOP Conference Series: Materials Science and Engineering* (Vol. 810, No. 1, p. 012061). IOP Publishing. **Scopus indexed.**
5. Loharkar, P.K. and Ingle, A., 2021. Microwave-assisted corrosion resistant pure polyester coating of cold rolled closed annealed steel. *Materials Today: Proceedings*, 44, pp.1676-1680. **Scopus indexed.**
6. Loharkar, P.K., Ingle, A. and Singh, H., 2022. Prediction of Temperature During Susceptor-Assisted Microwave Heating of Aluminum Using Parametric Simulation. In *Recent Advances in Industrial Production: Select Proceedings of ICEM 2020* (pp. 251-259). Springer Singapore.**Scopus indexed.**
7. Loharkar, P.K., Ingle, A. and Shivhare, S., 2021, September. PAni/Fe_3O_4 nanocomposite coating over cadmium using microwave energy. In *AIP Conference Proceedings* (Vol. 2369, No. 1, p. 020173). AIP Publishing LLC. **Scopus indexed.**

Patent Filed and published

1. Loharkar, P.K. and Ingle, A. Device for Joining of Materials using Microwave Energy. Application No. 202221021386. Publication date 22/04/2022.

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